

Public Interest Energy Research (PIER) Program
PROJECT REPORT

**Fault Detection and Diagnostics:
Moving the Market and
Informing Standards in California**

DRAFT



A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

Prepared for: California Energy Commission

MARCH, 2011

Prepared by: Western Cooling Efficiency Center

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PREFACE

The California Energy Commission Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

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For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

This document consists of three distinct reports:

- One crucial part of the prioritization of FDD tools is collecting intelligence from key stakeholders. In the first section of this report, A: Interviews with Key Stakeholders, we describe the process of developing an interview guide and carrying out a small set of interviews. We summarize the interviews that were held, as well as provide the detailed responses to our list of questions.
- In the second section of this report, B: FDD Prioritization, we identify nine different potential approaches, depending on the type of data collected (air side, refrigerant side, or electrical) and the type of model used for comparison with measurements (first principles, qualitative, history). We also identify the specific criteria that must be met to have a measure that is appropriate for inclusion in Title 24. These criteria include significant energy savings, cost effectiveness, prevalence of the fault being detected, probability that the fault will be fixed, reliability of detection, deployability, and other maintenance benefits.
- From this foundation, the team has developed draft standards for FDD in RTUs, suitable for inclusion in California's Title 24. This draft is presented in the third section of the report, C: Draft FDD Standards for Rooftop Units. An Industry Roundtable was held to get feedback on this draft, and the results of this Roundtable are summarized here.

Keywords: Rooftop unit, air conditioning, fault detection, diagnostics, Title 24, energy standards.

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- A. Interviews with Key Stakeholders**
- B. FDD Prioritization**
- C. Draft FDD Standard for Rooftop Units**

**Public Interest Energy Research (PIER) Program
PROJECT REPORT**

**Fault Detection and Diagnostics:
Moving the Market and Informing
Standards in California
A: Interviews with Key Stakeholders**



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Introduction

Objectives

The objectives of the overall Fault Detection And Diagnostics, Moving The Market And Informing Standards In California Deliverables project are:

- To identify appropriate technology for identifying and diagnosing faults in commercial building Rooftop HVAC Units (RTUs).
- To develop a proposal for a standard that would require this Fault Detection and Diagnostics (FDD) for Title 24.
- To get industry feedback on this proposal.
- To revise the proposal, and submit it to the Title 24 process.

Approach

Phase I

- Obtain input from industry stakeholders on desired capabilities of FDD tools and service models for making best use of FDD tools.

Phase II

- Identify the faults that occur in RTUs and their impact and frequency, to estimate the degree of savings made possible by FDD tools.
- Prioritize those faults to determine which are most likely to be cost effectively diagnosed and addressed.
- Identify diagnostic approaches that can be used to detect these faults.
- Define a set of criteria for the attributes an approach must have to be likely to be successful in the market place or to be successfully implemented in California's Title 24 energy code.
- Evaluate the potential approaches according to these criteria and identify potentially successful approaches, and describe the currently available tools that utilize these, and the Energy and Demand Savings potentially.

Phase III

- Create a "Minimum FDD Capability Requirements" document that summarizes and describes the requirements for a tool that could be incorporated in Title 24, including a description of the required functionality, and an outline of the acceptance tests that would be required to document installed functionality.
- Hold an Industry Roundtable to obtain industry feedback on this draft.

Phase IV

- Develop and submit a code proposal, and follow the CEC process to support the proposal.

In the second Phase of this project, “Fault Detection And Diagnostics, Moving The Market And Informing Standards In California Deliverables: B: FDD Prioritization,” we will identify and prioritize the faults that can be detected by a set of currently (or shortly) available diagnostic tools, and will evaluate the available tools.

One crucial part of this prioritization is collecting intelligence from key stakeholders. In this report, we describe the process of developing an interview guide and carrying out a small set of interviews. We summarize the interviews that were held, as well as provide the detailed responses to our list of questions.

In the third Phase, we will develop a draft specification for new requirements for FDD in Rooftop Units. We will also hold an industry roundtable to present the draft to a set of industry actors, and obtain their feedback. The following phase will consist of drafting a proposal for a standard and following the CEC Title 24 review process.

Background

Remote and automated Fault Detection and Diagnostic (FDD) tools have the potential to save considerable energy in California fleet of existing commercial rooftop air conditioning units (RTUs). The market for these systems has not yet materialized, however. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 70% of the commercial square footage in California, they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built up systems. However, in reality, they are even less efficient. Many market failures have led to a lack of quality in installation and maintenance of these units, and their performance is suffering. Most RTUs have some sort of fault that is increasing their energy use. If these faults could be found and addressed, then a significant energy savings could be realized.

Interview Guide

The WCEC and NBI team developed an interview guide, intended to gauge the acceptability of FDD tools for RTUs. The guide is provided in Attachment 1. The guide consists of three separate sections.

- *Section 1: What is your Service Business like?* This is intended to find out about typical service models, and the business environment into which FDD will have to fit. No mention is made in this section of FDD.
- *Section 2: Here's FDD...* This is intended to give the interview participants a common grounding in what is meant by FDD tools.
- *Section 3: How Do or Would You Use FDD?* This section is intended to establish whether or not the participant has used any FDD tools, and why or why not. It is also intended to identify the necessary characteristics that would make FDD usable by them.

Summary of Interviews

Two interviews were held on December 18 and December 21, 2009 respectively. Each of these interviews included two participants. Attachments 2 and 3 present the raw responses from the interview participants.

Some of the major themes that emerged from these interviews include:

What is your service business like?

- How important is the service contract?
 - Best business is through repeated relationship.
 - Maintenance contracts offer recurring revenue, business year round.
 - Referrals common.
 - Some firms offer a full coverage guarantee – ~3 times the price of maintenance
 - Retention rate is important.
 - It's hard to sell a maintenance contract.
 - Some firms offer a 2 year warranty on installation is customer signs a service contract.
 - Best arguments to get people enroll into a maintenance contract: routine vs crisis. Most agree, but still need to be economically persuasive. "we're taking care of it for you"
 - more of a collaborative work: ask you while planning yearly budgets, etc...
- What are the most common problems?
 - Belt problems, bearings, contactors, capacitors, fan motor, compressor, missing filters, filter change, low air, freezups, heat exchanger failure, expansion valve takes out compressor, refrigerant leaks, operating pressures.
 - Overcharging is a training issue.
 - Depends on the quality of maintenance.
 - It's possible to put sensors on everything, but would have more issues with the sensors than with the parts in the first place.
- Special notes on economizers?
 - It is the first thing you disable. Complexity vs. benefits: it costs \$500-1000 to fix it. If disabled: everybody gets what he wants. Possible because of cheap energy.
 - economizer working is quite complex. Setting it correctly is a challenge.
 - not noticed by the customer. Noticed during maintenance, or customer complaining about low cooling. Service technician: fresh air over dramatized. => need for less fresh air., ie less bills most of the time. Customers often prefer to have it disabled than fixing it.
 - if the customer knew the cost of disabling the economizer, it could be possible to make a value proposition. Right now they don't see the benefit. W: Long payback.
 - lack of public awareness. Have to do the check, hard to convince.
 - The customer is still comfortable, so it's a hard sell.
- How important is metering?
 - Car analogy: mpg information very educative.
 - Need a monetary conversion process: EER to \$. Hard to do with energy efficiency.

- Why would a customer replace a unit?
 - o Old and broken down (for example compressor out).
 - o Age and cost of repair taken into account. "Under 500\$ policy": if it costs less than \$500, repair it.
 - o In a house: 12 years and above compelling to replace it.
 - o Another significant cause could be a hard to fix coil failure.
 - o Window of opportunity with fluid change=> if some equipment is not on sale anymore, need to change the whole unit. More significant with split system, because each half is sold independently. If one needs to be replaced, and only the new refrigerant type is available, then the other needs replacement too.
 - o many units in a complex, for example. Can be planned during the year. Dismounted equipment used as spare for the rest of the units.
 - o On RTU, parts available for a long time. Fluid available. Concern for change if many RTUs at the same location and some are dead. All may be replaced to avoid a mix of refrigerants.
 - o Part of a building renovation. Reroof, ownership change, tenant change. Financial transaction already taking place. Part of the negotiation to extend or renew the lease. Depreciation calculation by large property owner.
 - o Customers do not consider energy operating costs directly, fixed/changed if broken. =>likely to go with the fastest repair. Energy efficiency is a secondary argument.
- What are the maintenance cost constraints?
 - o Can't bid 1 hour for preventive maintenance. Motivation: Try to avoid service call between now and next regular service.
 - o It's typical that a maintenance tech will get 20 hours/week to do service, and has to get as many customers as he can.
 - o typically 5-6 calls a day. Compressor replacement: 4 hrs, but simple maintenance and diagnostics: 4-6/day
 - o better diagnostics on the system makes you faster and more confident.
 - o we try to do 2-1/2 calls/day (<10 tons).
 - o 5 calls if they're simple, if its superheat pressure or economizer 3-4 per day.
- OEM's provide some things for diagnosing faulty operation. Not much on the cooling side. usually used by technicians if present, but not very predominant right now.

How do you or would you use FDD?

- Are you using tools now?
 - o Most organizations currently not using any kinds of tools like FDD
 - o One we interviewed worked with three tools in Air-Care Plus. They were hit and miss. A lot of the reports didn't make sense. It works better with small equipment (eg, temperature probes). Depends on ambient and return conditions. A lot of cables and connections. It's hard to be profitable. Existing customers will ask "why didn't you find it before?". It's good to use when doing compressor changeouts for refrigerant charge: we bought 2 tools on our own.
- What are the benefits to the customer?

- o Better interaction with the contractor. Shows professionalism.
 - o long term performance monitoring may help to “prepare” the client for heavier/preemptive interventions
- What would you like in a tool:
 - o an automated report generation every so often (month?) sent to a specific person.
 - o time it with energy bills so that customers are more aware.
 - o Do not overload clients/technicians with data
 - o An indication about performance, another one about energy consumption.
 - o Different information levels:
 - “idiot light”
 - alarm if efficiency goes under a certain threshold
 - efficiency for each unit
 - o Tool needs to be portable.
 - o log all activity
 - o Daily updates, although there’s a nuisance factor. Safeway, for example, gets Benchmark variance data, monthly on different variables.
- Will these tools reduce the number of service calls?
 - o Do not see any reduction of field trips: need to factor in false alarm
 - o am I avoiding more calls, or creating more calls? How many false positives?
 - o Each layer of complexity adds possible faults. => the increased maintenance may counterbalance all the energy benefits.
 - o On a service contract, false alarms as a cost for the contractor.
 - o The system must actually bring what it promises.
 - o A good solution should cost less than \$100
 - o Can’t reduce service calls to 2/year because of filters and belts.
- Would customers pay a 5-10% premium?
 - o Can see a premium of 10% for a very good field diagnostic device.
 - o If they have a critical environment.
 - o Need a more sophisticated customer.
- What type of customers would be most interested?
 - o Maintenance contract customers have a long term view, and do analysis on a whole building level.
 - o Higher end workers, like doctors/ lawyers would be most interested in this kind of service. High end restaurants. Retails with food safety issues
 - o process, server room, financial component is important.

Attachment 1: FDD Interview Guide

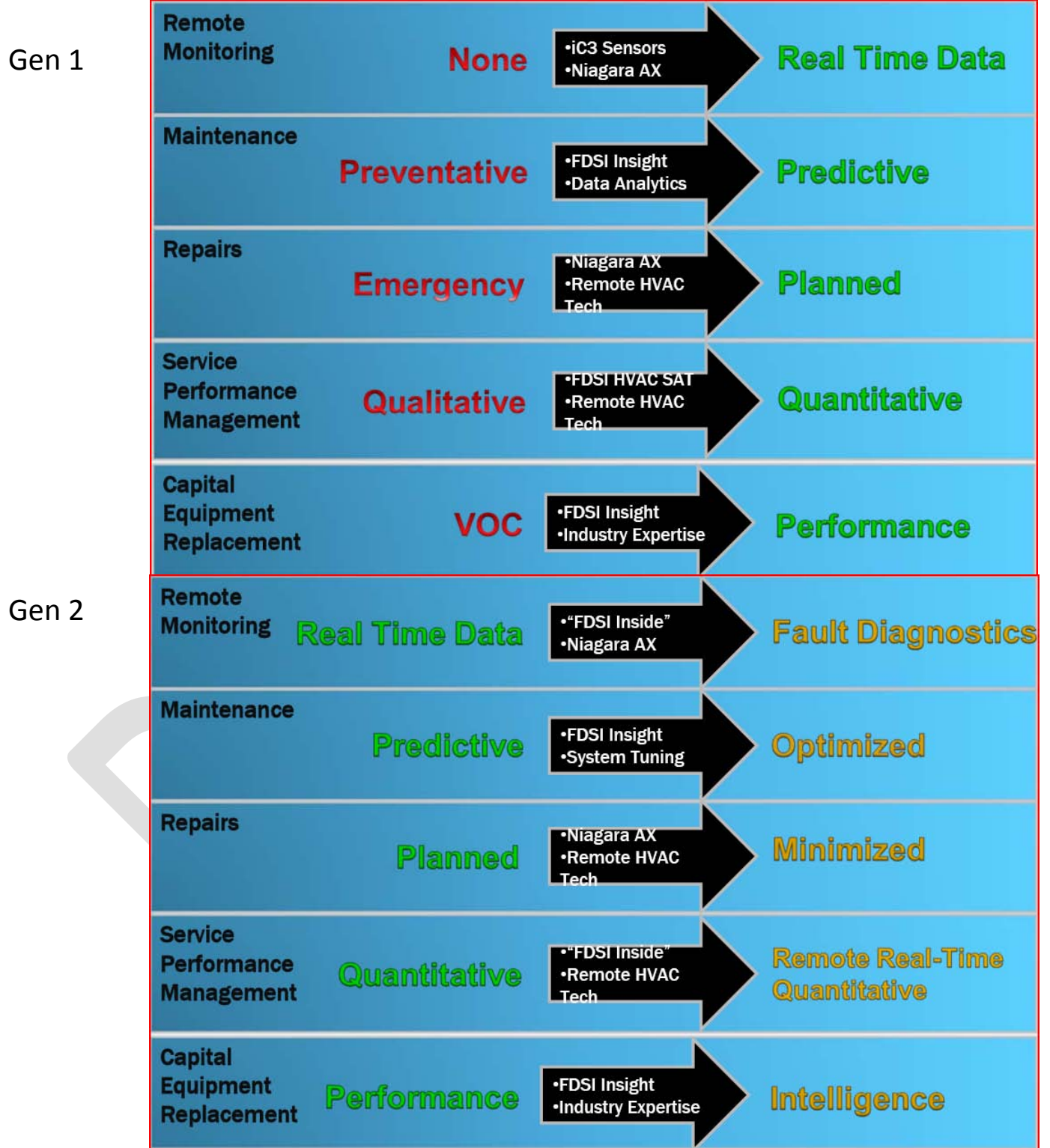
What is your service business like?

1. What constitutes RTU service in the field?
2. How is your service business structured?
3. What problems are the most common or the most important (why?) causes of service calls?
4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?
5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?
6. What is the nature of RTU service marketing [how is service marketed? How is service delivered- scheduled calls/on demand only for some/other? How is service linked to product sales]
7. What tools do your techs use to diagnose faulty or less-than-optimal performance?
8. What tools do the OEM's provide for diagnosing faulty operation?
9. What tools do the OEM's provide for performance monitoring?
10. Do your techs use these tools? If not, why not?
11. What (related to your RTU service business!) keeps you up at night?

Here's FDD...

Faults					
Categories	Hard fault		Degradation fault		Fault Prediction
	Loss of a function/whole unit		No loss of function, but not performing as expected		Identify a unit that is near the end of its useful life
	Sensors and Simple Alarms		Performance Monitoring		Characteristic performance metrics and Inspection
	Comfort not maintained		Models for symptoms or performance metrics		Models for symptoms and Inspection
	Fault is easy, cause may be more difficult		Need for specific procedure/tools		Fault is easy, cause may be more difficult
Annunciation		Technician during Service Call, or Remote to Service Center with Data Mining		Remote to Service Center	

Bank of America Intelligent Command and Control Center



How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?
2. Can you imagine using FDD tools in your service business? How? What's the business model? How would you change your service offering?
3. Would you be more interested in hard faults, degradation faults, or fault prediction?
4. Would you be more interested in monitoring, fault detection, or diagnostics?
5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, ...)
6. What value would it bring to your customer? (amount of energy savings, improved uptime,...)
7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)
8. How much would you be willing to pay to have this tool available?
9. What types of customers do you believe would be most interested in this kind of service?
10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]
11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?
12. What information would you like to see on an FDD/PM GUI/dashboard?
13. If you could design an RTU performance monitoring system with remote access, what would be included as features?
14. Do you have any customers who you think we should interview?

Attachment 2: Interview 1

Participants:

Erik Emblem (E) Cal SMACNA and Rick Wylie (W) Beutler Corp.

December 18, 2009

Background

E: A Consultant with the California Sheet Metal Workers. Contractor background 7 years service. 70% of the client's activity. Clients expectations: Reliability dependability consistency.

Union: 625 contractors in California, 50 union members.

From fabrication companies to HVAC global suppliers

W: Installation technician. Done some service work.

Maintenance intended as "maintenance agreement"

Commercial: more likely to see the value of maintenance. Some have their own maintenance staff (filter change, simple parts replacement, etc...)

What is your service business like?

1. What constitutes RTU service in the field?

W: on the phone, ask for show up cost. Some easy things can be fixed on the spot. For the rest, price proposition for fixing. No need for permits for part swaps

2. How is your service business structured?

W: Business through repeated relationship.

E: lot of contact through the internet. Relationship: established from quite some time (family recommendations: inter generational). Sticker on the heater.

Nate (?) study: demographics on the first call. => more feminized...

W: New commercial practices: price based competitive bid on maintenance contract.

If maintenance contract, typically repairs not taken into account, but discount applied. Some higher end /specific application may have a partial coverage of repairs.

3. What problems are the most common or the most important (why?) causes of service calls?

W: less leaks than in split systems. In order of occurrence: Belt problems, bearings, contactors, capacitors fan motor, compressor (rare but significant) Missing filters

Q: how do you know bearings are shot?

W: from the noise, can be seen. More generally, accurate service allows to see a lot

Q: what if it could be remotely detected?

W: possible to put sensors on everything, but would have more issues with the sensors than with the parts in the first place.

Q: What about economizer issues?

W: first thing you disable. Complexity vs. benefits: 500-1000\$ to fix it. If disabled: everybody gets what he wants. Possible bc cheap energy.

Q: snap disk thermostat; damper motor (question of Mark regarding the link btw snap disks and motors, not really understood)

W: whatever the piece, economizer working is quite complex. Setting it correctly is a challenge.

Q: does the customer asks to fix the economizer?

W: not noticed by the customer. Noticed during maintenance, or customer complaining about low cooling. Service technician: fresh air over dramatized. => need for less fresh air., ie less bills most of the time. Customers often prefer to have it disabled than fixing it.

E: if the customer knew the cost of disabling the economizer, it could be possible to make a value proposition. Right now they don't see the benefit. W: Long payback.

E: lack of public awareness. Have to do the check, hard to convince.

W: on the customer side, people would rather spend on a solar system, even if less efficient: importance on metering the production. Car analogy: mpg information very educative. Importance of metering. Monetary conversion process. EER to \$. Hard to do with energy efficiency?

4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?

W: 1- old and broken down (for example compressor out). Age and cost of repair taken into account. In a house: 12 years and above compelling to replace it. Another significant cause could be a hard to fix coil failure. Window of opportunity with fluid change=> if some equipment is not on sale anymore, need to change the whole unit. More significant with split system, because each half is sold independently. If one needs to be replaced, and only the new refrigerant type is available, then the other needs replacement too.

Other case: many units in a complex, for example. Can be planned during the year. Dismounted equipment used as spare for the rest of the units.

On RTU, parts available for a long time. Fluid available. Concern for change if many RTUs at the same location and some are dead. All may be replaced to avoid a mix of refrigerants.

2- part of a building renovation. Reroof, ownership change, tenant change. Financial transaction already taking place. Part of the negotiation to extend or renew the lease. Depreciation calculation by large property owner.

Q: how to assess the remaining life on the unit. Customers arrive with preconditioned ideas. Like, "under 500\$ policy".

Q: consider energy operating costs? W: not directly, fixed/changed if broken. =>likely to go with the fastest repair. Energy efficiency is a secondary argument.

E: Carfax like report: click a few things, and gives you a "number"

W: best customer: maintenance customer. Long term view. Analysis on a whole building level.

Q: what arguments to get people enroll into a maintenance contract.

W: routine vs crisis. Most agree, but still need to be economically persuasive. "we're taking care of it for you"

E: more of a collaborative work: ask you while planning yearly budgets, etc.

Q: advice for good deals?

E: give the clients the information they need

5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?

W: typically 5-6 calls a day. Compressor replacement: 4 hrs, but simple maintenance and diagnostics: 4-6/day

Q: productivity gains of integrated diagnostics?

W: better diagnostics on the system makes you faster and more confident.

6. What is the nature of RTU service marketing [how is service marketed? How is service delivered- scheduled calls/on demand only for some/other? How is service linked to product sales]

7. What tools do your techs use to diagnose faulty or less-than-optimal performance?

W: Temperature probe, gages, amp-meters. So much variation out there that it is tough to have a standardized protocol/tools. Some "art" is involved!

8. What tools do the OEM's provide for diagnosing faulty operation?

W: Some things provided on the controllers. Mainly on the furnace side. Not much on the cooling side. Usually used by technicians if present, but not very predominant right now.

9. What tools do the OEM's provide for performance monitoring?

10. Do your techs use these tools? If not, why not?

11. What (related to your RTU service business!) keeps you up at night?

W: Nothing specific to RTUs. More general business management: trained workers, customer interaction.

E: noise transfer can be an issue, but outside of this, no problem.

W: automated report generation every x (month?) sent to a specific person.

E: time it with energy bills so that customers are more aware.

W: on big businesses: numbers add up and it starts to be worth investing. And image issues.

How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?
No
2. Can you imagine using FDD tools in your service business? How? What's the business model? How would you change your service offering?
W: could be a benefit

E: depends on how it is packaged. Do not overload clients/technicians with data

Do not see any reduction of field trips: need to factor in false alarm

W: am I avoiding more calls, or creating more calls? How many false positives? Each layer of complexity adds possible faults. => the increased maintenance may counterbalance all the energy benefits. On a service contract, false alarms is a cost for the contractor.
3. Would you be more interested in hard faults, degradation faults, or fault prediction?
4. Would you be more interested in monitoring, fault detection, or diagnostics?
5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, ...)
E: No real reduction of trips expected (see 2)

W: Interventions may be more efficient. The system must actually bring what it promises.
6. What value would it bring to your customer? (amount of energy savings, improved uptime,...)
E: better interaction with the contractor. Shows professionalism.

W: long term performance monitoring may help to "prepare" the client for heavier/preemptive interventions
7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)
W: 10% for a very good field diagnostic device.
8. How much would you be willing to pay to have this tool available?
W: to many possible situations to give a figure
9. What types of customers do you believe would be most interested in this kind of service?

W: higher end workers, like doctors/ lawyers. High-end restaurants. Retails with food safety issues

10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]

W: only way to justify an added cost. If technician has to show up, even a good solution should cost less than \$100 (see 7)

11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?

12. What information would you like to see on an FDD/PM GUI/dashboard?

W: An indication about performance, another one about energy consumption.

13. If you could design an RTU performance monitoring system with remote access, what would be included as features?

E-W: Different information levels:

-“idiot light”

- alarm if efficiency goes under a certain threshold

- efficiency for each unit

- log all activity

14. Do you have any customers who you think we should interview?

E: see about national restaurant association

Attachment 3: Interview 2

Participants:

Denny Mann (D) Marina Mechanical and Russ Donicci (R) Mechanical Air Service

December 21, 2009

Background

D: Service (\$4Million) and Construction

R: \$2Million business, 80% construction. Residential component is high end. Service, retrofit, clean rooms. 60% new, 40% service

What is your service business like?

1. What constitutes RTU service in the field?

D: Maintenance contracts, recurring revenue, business year round. General operations for retrofit. Commercial, light industrial. Not much refrigeration. 14 trucks. Total cost not hourly rate. Contract <100,000 sqft. Unless on staff, 95% on contract.

R: It's hard to get a maintenance contract.

2. How is your service business structured?

D: referrals common. Contract for 4 times per year. \$500 pre approved, avoids truck roll. Full coverage guarantee – 3 times the price of maintenance.

Q: Callbacks different between manufacturers?

D: No. Tho a few years ago York had >20%.

D: we provide a Warranty of 1 year

R: Tenant aggravation, maintenance is often a "loss leader", where contractors do bad installs and make up on service. It's typical that a maintenance tech will get 20 hours/week to do service, and has to get as many customers as he can.

3. What problems are the most common or the most important (why?) causes of service calls?

D: Non-PM: filter, low air, freezups, heat exchanger failure. Depends on the quality of maintenance. Can't bid 1 hour for preventive maintenance. Motivation: Try to avoid service call between now and next regular service.

See study by Jones Long LaSalle, BOMA Studies.

R: Electrical, contactors, expansion valve takes out compressor, refrigerant leaks, operating pressures. Training issue: don't overcharge.

D: Economizers, it costs \$100 to fix the actuator. The customer is still comfortable, so it's a hard sell. We use Honeywell software. We talked with Adrienne Thomle, the 7650 costs \$20 and the 7660 costs \$24.

4. Have you ever told an owner that their RTU was on its last legs? What symptom were you responding to? What did the customer say? What data did you need to make this call and convince the owner?
5. How long is a typical service call/how many service calls can a technician make in a day? What influences this?

R: budget for capital improvement. 20% energy savings. Good relationship – fan was looking wornout and there was bearing noise. Checked on parts availability, reduced disruption for tenants. Other contractors are looking for what you missed.

D: we try to do 2-1/2 calls/day (<10 tons).

R: 5 calls if they're simple, if its superheat pressure or economizer 3-4 per day.

6. What is the nature of RTU service marketing [how is service marketed? How is service delivered- scheduled calls/on demand only for some/other? How is service linked to product sales]
7. What tools do your techs use to diagnose faulty or less-than-optimal performance?
D: worked with three tools in Air-Care Plus. They were hit and miss. A lot of the reports didn't make sense. It works better with small equipment (eg, temperature probes). Depends on ambient and return conditions. A lot of cables and connections. It's hard to be profitable. Existing customers will ask "why didn't you find it before?". It's good to use when doing compressor changeouts for refrigerant charge: we bought 2 tools on our own.
8. What tools do the OEM's provide for diagnosing faulty operation?
The new Lennox RTU tells you when it went off on high head, delta T on coil, pressures of system.
9. What tools do the OEM's provide for performance monitoring?
10. Do your techs use these tools? If not, why not?
11. What (related to your RTU service business!) keeps you up at night?

How do you or would you use FDD?

1. Are you or your organization currently using any kinds of tools like FDD?
D: We use Service Assistant
R: we use thermal imaging
2. Can you imagine using FDD tools in your service business? How? What's the business model? How would you change your service offering?
R: some customers maintain different things. Degradation, re remote service assistant. Change more level of service. Clerk can't interpret data. Customer: predictive, downtime, energy costs. We are trying to get into the energy component.
AB1103 requires the Energy Star Rating, it's hard to get things like the number of PCs. Carbon footprint is a motivator. Need a 5 year SPT on equipment. Would customers pay a 5-10% premium? If they have a critical environment. Retention rate is important. Need a more sophisticated customer. Service assistant \$3000. Tool needs to be portable. Can't reduce service calls to 2/year because of filters and belts. We offer a 2 year warranty on installation is customer signs a service contract.

3. Would you be more interested in hard faults, degradation faults, or fault prediction?
4. Would you be more interested in monitoring, fault detection, or diagnostics?
5. What value would it bring to you? (reduce the number of trips required, reduce the length of a service call, ...)
6. What value would it bring to your customer? (amount of energy savings, improved uptime,...)
7. How much of a premium would your customers be willing to pay, (or how much of a discount would they need to see), to be provided this service? (One time capital cost/ monthly/ quarterly/ annual fee-based?)
8. How much would you be willing to pay to have this tool available?
9. What types of customers do you believe would be most interested in this kind of service?
D: process, server room, financial component is important.
10. Would you be interested in remote monitoring of RTUs? [dependent on customer size or would you like for all customers?]
11. What performance monitoring/FDD information do you think are most important in terms of optimizing performance/efficiency?
D: Service assistant type information: performance, efficiency, Supply and return temps, amps on components to confirm what's running. Go back and look at trends
12. What information would you like to see on an FDD/PM GUI/dashboard?
D: Daily updates, although there's a nuisance factor. Safeway, for example, gets Benchmark variance data, monthly on different variables. Need to know how to use Carrier alarms.

R: Traiing: manufacturer school if it's worthwhile, then teach what you learned.
13. If you could design an RTU performance monitoring system with remote access, what would be included as features?
14. Do you have any customers who you think we should interview?
Kevin Napper, Safeway

DRAFT

**Public Interest Energy Research (PIER) Program
PROJECT REPORT**

**Fault Detection and Diagnostics:
Moving the Market and
Informing Standards in California
B: FDD Prioritization**



A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

Prepared for: California Energy Commission
Prepared by: Western Cooling Efficiency Center

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1. Introduction

In this second Phase of this project, “Fault Detection And Diagnostics, Moving The Market And Informing Standards In California Deliverables: B: FDD Prioritization,” we identify and prioritize the faults that can be detected by a set of currently (or shortly) available diagnostic tools, and evaluate the available tools.

In the next Phase, we will develop a draft specification for new requirements for FDD in Rooftop Units. We will also hold an industry roundtable to present the draft to a set of industry actors, and obtain their feedback. The following phase will consist of drafting a proposal for a standard and following the CEC Title 24 review process.

Background

Remote and automated Fault Detection and Diagnostic (FDD) tools have the potential to save considerable energy in California’s fleet of existing commercial rooftop air conditioning units (RTUs). The market for these systems has not yet materialized, however. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 70% of the commercial square footage in California, they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built up systems. However, in reality, they are even less efficient. Many market failures have led to a lack of quality in installation and maintenance of these units, and their performance is suffering. Most RTUs have some sort of fault that is increasing their energy use. If these faults could be found and addressed, then a significant energy savings could be realized.

This report summarizes the activities that fulfill Objectives 1-5 as described in “Introduction to Project 5.3.” It documents the results of a thorough literature search and a set of interviews that shed light on the faults that occur in RTUs and on the potential approaches to detecting these faults. It starts by describing the faults that affect RTUs, in terms of their frequency and their potential for energy savings. A set of criteria are then proposed according to which the approaches are then evaluated. It then describes and classifies various approaches to detecting faults, providing examples of existing tools where available. Finally, a set of prioritized approaches is identified, which will guide the later development of a set of minimum attributes of a tool that could be adopted into code.

2. Faults that Affect RTUs

In this section, the different faults affecting RTUs will be described. For these faults, data regarding the prevalence and energy efficiency impact will be presented.

The information regarding the *prevalence* of faults on this paragraph is quoted from Cowan 2004, “Review of Recent Commercial Roof Top Unit Field Studies in the Pacific Northwest and California”. This study gathers data from previously completed research projects. Slightly over 500 units in 181 locations have been inspected during these different field studies, all located in California and the North West. This gives a very relevant set of data for our purpose. These data are shown in Table 1.

Table 1: Frequency of some Common Faults in Rooftop Air Conditioners (Cowan 2004).

Fault	Fault Level	Frequency Found
Economizer Malfunction	Various faults	64%
Refrigerant Undercharge/ Overcharge	>5%	46%
Inadequate Airflow	<300 cfm/ton	42%
Failed Sensors	Various faults	20%

The information regarding the *energy impact* of each fault comes from Breuker and Braun, 1998, "Common Faults and their Impact for Rooftop Air Conditioners." In this study, different common faults were artificially introduced in an RTU and the impact on energy efficiency and COP was evaluated. Table 2 shows the results that Breuker and Braun found.

Table 2: Energy Impacts of some Common Faults in Rooftop Air Conditioners (Breuker and Braun 1998).

Fault	Fault Level	% Change in capacity	% Change in COP
Compressor Valve Leakage	35% $\Delta\eta_v$	-21.3	-23.8
Condenser Coil Fouling	35% area blocked	-21.3	-23.8
Inadequate Airflow	36% Δ airflow	-19.4	-17.4
Liquid Line Restriction	20% ΔP	-17.2	-8.7
Refrigerant Undercharge/ Overcharge	14% undercharge	-8	-4.6
Economizer Malfunction			Up to 40%
Thermostat Errors			Up to 40%
Failed Sensor			Up to 40%

2.1. Mechanical Faults

2.1.1. Compressor valve leakage

When slugs of liquid refrigerant enter the compressor, the compressor valves can be damaged. If the sealing becomes less effective, high pressure refrigerant can either:

- Leak back into the suction line across the suction valve, or
- Leak back into cylinder across the discharge valve.

This corresponds to a loss of volumetric efficiency, the impacts of which on efficiency and COP have been evaluated by in Breuker and Braun 1998.

2.1.2. Condenser coil fouling

This fault is caused by a buildup of debris on the condenser coil. This limits the available condenser coil area and reduces heat transfer and the total airflow across the coil.

2.1.3. Inadequate Airflow

This is caused by a buildup of debris on the evaporator coil or other restrictions in the airpath. The consequences are twofold: the airflow across the evaporator is reduced and the heat exchange efficiency is limited. The impact of the second effect is limited, though.

Airflow has been found to be deficient in 42% of the cases. The following criterion has been used: the airflow is considered too low under 300CFM/ton, to be compared with the 400CFM/ton used for industry efficiency ratings.

2.1.4. Liquid line restriction

This fault occurs when a filter/dryer or expansion device is obstructed by debris. This increases the total pressure loss in the liquid line.

2.1.5. Refrigerant leakage/undercharge/overcharge

This fault can either be caused by a slow leak in the system or by the wrong amount of refrigerant introduced into the system. Charge assessment is not straightforward, and the different methods available and contractor practices explain that this is a very common problem in the field.

In the documented sample, 46% of units present a charge outside of a $\pm 5\%$ acceptance range. Energy savings impacts found by Breuker and Braun were up to about 5% for a 15% error in charge. Other researchers looked at higher levels of charge error, and found even greater energy impacts. For example, Robert Mowris recently tested a residential air conditioner, and found upwards of 65% efficiency loss in a unit that was 40% undercharged. (Personal communication with Robert Mowris, 2010). Regardless of the energy savings, the greenhouse gas reduction potential of detecting refrigerant leakage is substantial.

2.2. Controls Faults

2.2.1. Short cycling

Nominal efficiency of air conditioning is only reached after a few minutes of operation, due to thermal transients. Since most systems operate with “on-off” control, at partial loads, the unit will naturally cycle between “On” and “Off” phases. If this cycling sequence is too short, though, the unit stops working before even reaching an acceptable efficiency, with a great impact on energy consumption.

This problem can be due to a bad thermostat setting or oversizing.

2.2.2. Economizer malfunction

On average, 64% of the units of the sample presented some kind of economizer failure or tuning problem. Different faults can be observed:

- Broken, frozen or missing drive system components
- Outside air or mixed air sensor failure
- Faulty repairs
- Low changeover temperature setpoint
- Use of a single-stage cooling thermostat

The energy impact can be estimated between 14 and 40%, according to whether the economizer is malfunctioning or not functioning at all.

2.2.3. Thermostat errors

- Improper thermostat (single-stage cooling only)
- Cycling fans during occupied periods

- Continuous fans during unoccupied periods
- Improperly installed resistors
- No nighttime setup or setback

Savings can vary. Correcting cycling fans during occupied periods will even increase the energy use (but improve indoor air quality). The highest savings, up to 40%, will occur when the thermostat is preventing the economizer from operating.

2.2.4. Failed sensor

This problem has been noted in 20% of the units. The energy savings for repairing sensors vary over a wide range. They can be modest if the value is slightly incorrect, but can go up to 40% if they enable a non functioning economizer

3. Criteria for Evaluating FDD Approaches

In order for an FDD approach to be viable in the market and to be justifiably included in Title 24, it must meet several criteria. The primary criteria for Title 24 are energy savings and cost effectiveness. The primary criteria for the market are somewhat different, however. To be successfully marketed, the tool must be low cost, marketable, and reliably detect important problems in buildings. Of course, the role of codes is to get building owners to implement measures that the market for some reason or another is not successfully providing. This would suggest that even if a product does not meet marketability criteria, it can still be effectively implemented in Title 24, so long as it meets the criteria for code inclusion.

Ideally, we would provide actual numerical metrics for these criteria. It should be noted, however, that most of the criteria are quite difficult to assess (particularly when we are discussing “hypothetical” tools). Diagnostic tools in general are difficult to assess because it is never known ahead of time how many and what type of faults will be detected. It is beyond the scope of this project to provide quantifiable metrics for each criterion. It should be possible, however, to compare different tools and describe characteristics somewhat qualitatively. When we evaluate the different approaches, we use a scale of High, Moderate, or Low to describe whether the criteria are met Fully, Partially, or Not at all.

3.1. Magnitude of Energy Savings

The energy savings expected from an FDD approach depends entirely on the type and number of faults that can be detected and addressed. Reductions in greenhouse gas emissions go along with these energy savings¹. Some of the faults that RTUs experience are indicated below, along with an indication of the relative magnitude of energy savings possible through remedying the faults.

High:

- Compressor valve leakage

¹ Of course, HVAC refrigerants currently in use are themselves notable sources of greenhouse gases, and the detection of leaks when they occur can provide as significant, if not more significant a reduction in greenhouse gasses.

- Condenser coil Fouling
- Inadequate airflow
- Economizer malfunction
- Economizer misapplied
- Other controls problems.

Moderate:

- Refrigerant leakage/undercharge/overcharge
- Liquid line restriction.

Low:

- Short cycling

3.2. Cost Effectiveness

The cost effectiveness² of a diagnostic approach is dependent upon the potential savings, of course. But it is also dependent upon the cost to implement the method. The cost is based upon the type of data that is required, the overall number of points required, any processing capabilities that must be added, and communications hardware and access.

The principal cost incurred for FDD is for data collection. Depending on the method that is used, existing sensors installed in the RTU might be used. Care must be taken to ensure that the sensors are of sufficient accuracy and are installed in the appropriate location. In some cases, redundant sensors might be needed to take the place of the existing sensors. The cost effectiveness of some of the sensors that are typically used are:

High:

- Fan On/Off
- Compressor On/Off
- Operating Mode: Cooling/Heating/Ventilation
- Outdoor Air Damper Position
- Current/kW

Moderate:

- Suction temperature
- Liquid temperature
- kWh

² Defined as the life-cycle Net Present Value of the incremental benefit of the technology (including the time-dependent value of reduced energy consumption, maintenance costs, and quantifiable non-energy benefits such as improved comfort), divided by the sum of the incremental first costs and Net Present Value of all other incremental costs associated with the technology (including maintenance costs and costs of remediation of faults).

Low:

- Ambient temperature
- Return air temperature
- Supply air temperature
- Static Pressure
- Suction pressure
- Liquid pressure
- Discharge Pressure
- Power factor
- Power quality

Processing of diagnostic algorithms can take place in the onboard controller, on an installed PC, or remotely. Even when a PC or remote computer is used, there may still be a need for on-site signal processing to reduce the data and pre-process them. In most cases, these processing platforms do not contribute significantly to the cost. For some methods, however, it will be significant.

High: An approach that uses an EMS platform for processing

Moderate: An approach that that can be accomplished by an embedded controller

Low: An approach that can be accomplished only with use of an added PC or processor.

The defined scope for this program is remote diagnostics, so all approaches considered here will require remote communications. For remote diagnostics, communications hardware and access are required. This can be accomplished by tying into the building's Energy Management System, or installing a dedicated modem and phone line. It is often possible to use a gateway to allow the diagnostic module to piggy-back on the building's communications infrastructure to reach the internet.

3.3. Frequency of Fault

A diagnostic tool is not as useful if it only detects faults that occur rarely. The more common the fault is that it detects, the more appropriate it is for Title 24. The faults that are frequent in RTUs are described in Table 1 and are provided below, along with an assessment of their relative frequency.

High:

- Inadequate airflow
- Refrigerant leakage/undercharge/overcharge
- Economizer malfunction
- Economizer misapplied

Moderate:

- Condenser coil fouling
- Short cycling
- Other controls problems

- Locked rotor
- Liquid line restriction
- Liquid slugging: Moderate.

Low:

- Loss of phase
- Unbalanced voltage
- Compressor valve leakage
- Flooded start.

3.4. Probability that Fault will Get Fixed

It is easy to envision a code that requires manufacturers to install one of these types of FDD in their units in the factory, or contractors to install “after-market” tools that will identify faults.

However, it is somewhat more difficult to envision how these tools can be guaranteed to provide savings. After all, they merely note the fact that a fault exists, they do not fix it. Some method must be found to increase the probability that faults will be fixed.

Tools that diagnose problems that are likely to be fixed will be more likely to result in savings, so they are more likely to be successful in being implemented in code.

High:

- Refrigerant leakage/undercharge/overcharge
- Condenser coil fouling
- Inadequate airflow
- Liquid line restriction
- Other controls problems
- Locked rotor

Moderate:

- Liquid slugging
- Compressor valve leakage
- Economizer misapplied
- Economizer malfunction

Low:

- Loss of phase
- Unbalanced voltage
- Flooded start
- Short cycling

3.5. Reliability, Robustness

Reliability and robustness in a FDD tool refers to a number of factors that influence whether a tool can be expected to work well over time. Some of these factors are:

- How difficult is it to install the tool? Installation errors such as placing sensors in the wrong location or mounting them incorrectly can render a FDD tool useless. How prone is the tool to misinstallation? Airside sensors can be difficult to install correctly, and care must be taken to mount them in the correct location so that they accurately reflect the temperature of an entire air-stream. Refrigerant sensors are somewhat less difficult, but they are also prone to mounting errors, as when temperature sensors are not mounted in direct enough contact with the lines being measured.
- Does the tool require maintenance? Some sensors, such as RH sensors and Pressure gauges require periodic calibration. Any tool that requires such maintenance will be less robust than tools with maintenance free sensors.
- A tool is only useful to a customer or technician if its rate of false alarms is minimized, as well as the rate of missed diagnoses. False alarms are a serious problem in FDD tools, and anything that generates unreliable alarms and causes alarm overload will not be used for long. Similarly, if a tool cannot be counted on to detect when a system is failing, it cannot be relied upon to provide remote diagnostics. This delicate balance must be found for every tool and every type of fault detected.

High: No maintenance is required, no installation required, or false positives and negatives are both minimized.

Moderate: Minimal maintenance required, installation is easy to perform, moderate level of false positives and negatives.

Low: Significant maintenance required, installation prone to errors, high false positives or negatives.

3.6. Ease of Deployment

FDD tools can be deployed in many different ways. Three deployment models are described.

Performance monitoring:

Ongoing optimization of the use of the unit for a given environment can be referred to as Performance Monitoring. Many FDD tools can be deployed in this way.

Commissioning:

Commissioning refers to a process of evaluating if a newly installed or existing unit is performing as expected. It is a one-time intervention where a technician is on-site, so it does not require remote access. FDD tools used in commissioning typically do not require historical data, although Performance Monitoring data can be used to supplement the commissioning tool. It is difficult to envision how commissioning tools would be included as a requirement in Title 24, unless commissioning interventions were also required.

There are already tools available that assist service providers in diagnosing a system in the context of a commissioning-like process. The Honeywell Service Assistant, provided to the market by various California utilities through their “Air Care Plus” programs, is one example. It is difficult to imagine the building code requiring an intervention such as this, although it could require enabling technology that would make these kinds of interventions possible. They would not generate savings on their own, however.

Maintenance:

Avoid failures or degraded operation and optimize running costs by optimizing the maintenance operations.

The match between these situations and the available FDD methods (described later in section 4) can be summed up as follows in Table 3:

Table 3: Assessment of Deployment Capability for Different Types of Models

Deployment Method	Quantitative	Qualitative	Timeseries
Performance monitoring	High	Moderate	Moderate
Commissioning	High	Moderate	Low
Maintenance	High	High	High

Quantitative approaches seem to give the best performance but their use in the field seems unlikely due to the complexity and computational costs associated with them.

The other two types of approaches should be able to provide the required performance for the maintenance deployment but will provide very different results in term of commissioning and operation optimization.

Since the process timeseries method relies on previously logged data, it will not be able to detect any fault initially present in the system. This is quite a big limitation since much anecdotal evidence seems to show that errors are often introduced in the system during the installation of the units.

A qualitative model, on the other hand, does not rely on a baseline operating condition to evaluate the behavior of the system and could therefore diagnose errors at any time of the lifecycle of the unit.

The performance monitoring aspect, though, being linked to numerical values of efficiency criteria, cannot be included in a qualitative model, whereas a process timeseries based model can definitely detect a variation of performances due to an operation optimization.

If neither commissioning nor operation behavior evaluation want to be left aside, some hybrid approach combining both methods could be envisioned.

3.7. Other Maintenance Benefits

While not valued in the cost-benefit analysis done for Title 24, most FDD tools also provide maintenance benefits to the customer, service contractor, or both. This is key to marketability of FDD. The value of some of the maintenance benefits are:

High:

- Allowing contractors to send the right technicians with the right tools. By diagnosing problems remotely, the contractor can plan for a service call more accurately. This saves time and travel costs by avoiding second trips.
- Increasing uptime for customers, many of whom would suffer great financial losses if the RTU were to go down. A service that can avoid system failures would provide a great benefit to a Customer, and a great differentiator for a Contractor, who could charge a premium rate for this advanced service.
- Ensuring that maintenance or service is done correctly, to avoid callbacks. Unbillable callbacks are a real drain on contractors' bottom line. An example of this is systems that can ensure that charge has been adjusted correctly.

Moderate:

- Reducing the frequency of required maintenance by annunciating when maintenance is required. While this would seem to be a benefit to service contractors, those interviewed for this study indicated that they would not be likely to rely on this and would provide service calls on the usual schedule. They might reduce unscheduled maintenance, however.
- Allowing maintenance to be provided remotely. By assessing the condition of a system remotely, a service technician might be able to provide service to the customer over the phone, or even to make changes in controls remotely. This reduces unscheduled maintenance calls.

Low:

- Reducing the time required for a service call. A diagnostic tool that helped a service technician to do his or her job on the roof will have a benefit in reducing the time for a particular job. This is not as great a benefit as avoiding a service call, but if it allows for more jobs per day it is a benefit.

4. Definition of FDD Approaches

With a good understanding now of the criteria for selecting appropriate FDD tools, we now turn our focus to potential FDD solutions adapted to rooftop packaged air conditioning systems and heat pumps from 5 to 50 tons. All of the listed solutions may not be available on the market; the goal is to give the broadest possible view of the different approaches.

The objective of an FDD system is to detect faults early, diagnosis their causes, and enable correction of the faults before additional damage to the system or loss of service occurs. This is accomplished by continuously monitoring the operating conditions and comparing them to a model of expected performance. When actual measured operation does not match expectations determined with use of a

model, a fault is detected. Ultimately, the objective is to ensure that the building owner or operator will respond in an appropriate manner, remedying the problem.

We will define a method of classifying different approaches to FDD, and evaluate their potential for use in the market or in Title 24 Building Standards.

4.1. Classification of FDD Tools

There are two ways of characterizing FDD tools: one is based on the set of measured data points the tool uses to perform its analysis, another is to look at what sort of model is used to determine expected performance. Each of these factors has a strong influence on the final capabilities of the system.

4.1.1. Classification Based on Input Data

The input data acquired naturally falls into three distinct groups: Airside Data, Refrigerant Cycle Data, and Power Data.

Air side

- outdoor-air dry-bulb temperature
- return-air dry-bulb temperature
- mixed-air dry-bulb temperature
- outdoor air damper-position signal
- supply-fan status
- heating/cooling mode
- Outdoor air relative humidity (for enthalpy based economizers)
- Return air relative humidity (for differential enthalpy controls)

Refrigeration cycle

- Suction pressure
- Liquid pressure
- Discharge Pressure
- Suction temperature
- Liquid temperature
- Ambient temperature
- Return air temperature
- Supply air temperature

Some methods substitute the pressure monitoring with additional temperature sensors (Breuker and Braun 1998b).

Power Monitoring

- Fan, Compressor, or RTU kW
- kWh

- Power factor
- Real and reactive power
- Power quality

4.1.2. Classification Based on FDD Model

The different approaches can also be characterized by the models used to determine expected performance. For example for a first principle based or engineering model, physical laws are used to predict the behavior of the system. On the other end of the spectrum, black box models rely only on data from the process itself, and the resulting model may not have any physical significance. Table 4 illustrates some of the pros and cons of the different methods.

Quantitative models

Quantitative models are directly based on the physics of the process under consideration. According to the degree of complexity, they can either be steady state, linear dynamic or non linear dynamic. In this case, for a given set of measured inputs (temperature, pressure, ...) it is possible to calculate the expected behavior and compare it to the measured performances of the system (analytical redundancy). The differences (residuals) can then be evaluated to detect any fault within the system.

Qualitative models

Qualitative models can be based on a set of rules (inferred from the physics or expert knowledge), or qualitative physics instead of relying on quantitative mathematical relationships. Since measurement techniques usually provide quantitative inputs (temperature...) some preprocessing is often required to convert this information into qualitative inputs. One of the methods that can be used is for example fuzzy logic and other kinds of classifiers.

In the case of a rule-based modeling technique, a set of if-then-else rules are derived from a priori knowledge.

In expert systems, the rules are derived from insight, knowledge or guidance of people with expertise in the field. Another method is to derive the rules from a first principle approach, implemented in a tree structure within the software. Data gathered during the system operation allows navigating the decision tree and reaching a conclusion about the unit's behavior.

Models derived from process timeseries

This approach is entirely data driven: a known set of input and output data is fed to the system which then tries to find a mathematical relation between the two. This is called parameter extraction. Two different approaches coexist: if these parameters have no physical meaning, the approach is qualified as "black box." If the choice of parameters is based on a first principle approach and their value is obtained through linear regression from the set of data, we speak about a "grey box" approach instead.

Various methods exist for both approaches. The main difference between the two lies in their abilities to make predictions outside of the training data range.

4.2. Definition of FDD Approaches

We defined in the first part two ways of categorizing FDD systems: by the type of data required, and by the type of model used. When combining this information, we can define an FDD Approach Matrix where in which almost any possible FDD approach can be located, in Figure 1.

Type of Model	Strengths	Weaknesses	Suitability for FDD
Quantitative Models	- based on sound physics - most accurate estimators of outputs if well formulated - detailed models can also simulate faulty operation for easier detection - allow the modeling of transients	- complex and computationally intensive - significant development effort - many required inputs, some not readily available - sensitivity to poor user inputs	- detailed models unlikely to be a solution of choice - simplified models may be used
Qualitative Models	- well suited for data-rich environments - simple to develop and apply - transparent reasoning, works under uncertainties - ability to provide explanations for diagnostics because relies on cause-effect relationships - some methods do not require special knowledge of the system and accurate data	- specific to a system or process - difficult to find a complete, applicable set of rules, mostly for complex systems - simplicity can be lot as new rules are introduced - depends on the expertise of the developer	- may prove a good choice if quantitative approaches too demanding - good for one-time assessments
Process Timeseries Based Models	- well suited if theoretical models are unavailable/inaccurate - well suited if training data is abundant/cheap - no previous understanding of the system physics required for black box models - usually low computational requirements - theoretical foundations widely documented	- gray box models require a good process knowledge and statistic expertise - low performances outside of the training data range - large amount of data for all expected operation modes required - models are specific to a system - takes time to collect a training dataset - requires a training set representing correct operation	- suitable where no other method exists - lower cost than some methods - good for long-term assessments

Table 4: Strengths and Weaknesses of FDD Models

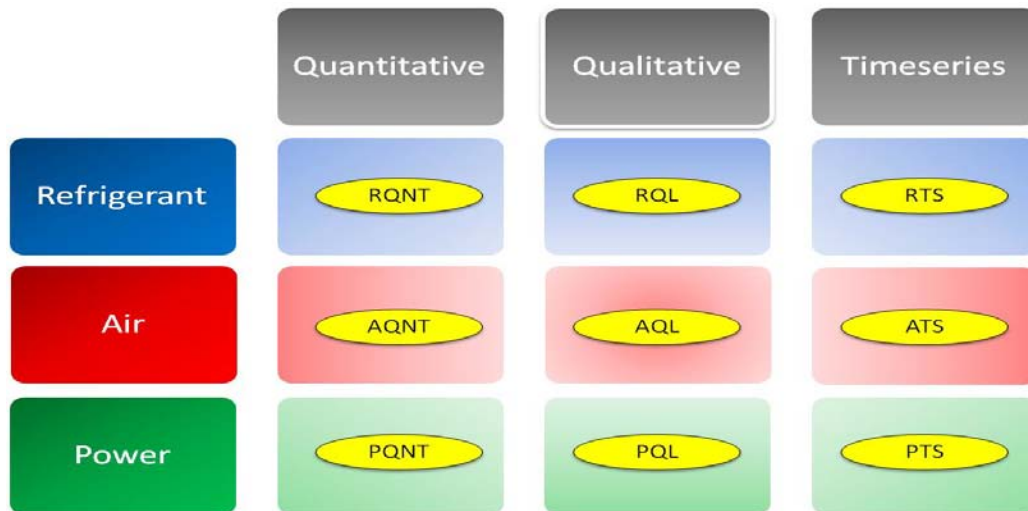


Figure 1: FDD Approach Matrix, Used to Classify FDD Approaches

Each cell in this matrix will be studied in detail. Most cells do not represent available tools, but one can still envision what the characteristics of tools would be in these cells. The sections that follow describe these “hypothetical” approaches in detail. Where there are actual tools available, they will be cited as examples and described. By evaluating hypothetical approaches, we can identify which would have the potential for appropriate tools and for Title 24. This will simplify the search for appropriate tools by allowing us to focus on a smaller set of tools.

4.3. Description of Available and Developing Tools

There are very few tools currently on the market. A handful of other tools have been piloted but have not yet been introduced to the market as viable products, and yet others are under development. While we will discuss the approaches that can be taken to FDD in a generic “hypothetical” way, it is useful to describe the tools that are commercially available, available in pilot status only, or in the pipeline. Tables 5 through 7 describe the type, the faults detected by each, and the required input data, respectively. Information is shown for “Basic” diagnostics (that implemented in the standard version of each tool) and “Extended” diagnostics (that implemented in potential extended versions). Each of these tools is described more later.

Table 5: Available Tools

Tool Name	Data	Model	Status	Developer
FDSI Insight V.1	Refrigerant	Quantitative	Available	Field Diagnostics, Inc
Sentinel/Insight	Refrigerant	Quantitative	Beta	Field Diagnostics, Inc
ClimaCheck	Refrigerant	Quantitative	Available	ClimaCheck Inc.
SMDS	Air	Qualitative	Pilot	Pacific Northwest National Lab
Sensus MI	Air	Qualitative	Available	University of Nebraska
NILM	Power	Qualitative	Pilot	Massachusetts Institute of Technology
Low Cost NILM	Power	Timeseries	Pilot	Massachusetts Institute of Technology
Virtjoule	Power	Timeseries	Developing	Virtjoule Inc.
Low Cost SMDS	Air-Power	Timeseries	Developing	Pacific Northwest National Lab

Table 6: Faults Detected by Available Tools

O	Basic FDD
X	Extended FDD

	FDS Insight V.1 Production	Sensus MI	ClimaCheck	SMDS	NILM	Low Cost NILM	Sentinel/Insight Beta Testing	Virtjoule	Low Cost SMDS
Low Airflow	O	O	O		O	O	O	O	
Low/High Charge		O	O		O	O	O	O	
Sensor Malfunction	O	X	O	O			O	X	
Economizer not Functioning	O	X	X	O			O	O	
Compressor Short Cycling	O	X	O		O	O	O	O	O
Excessive Operating Hours	O	X	O				O	O	O
Performance Degradation		O	O	O	O	O	O	O	O
Insufficient Capacity	O	X	O				O	X	O
Incorrect Control Sequence	O	X	O		O	O	O	O	
Lack of Ventilation	O	X		O			O	X	
Unnecessary Outdoor Air	O	X	X	O			O	X	
Control Problems	O	X	O	O			O	O	
Failed Compressor	O	O	O	O	O	O	O	O	
Stuck Damper	O	O	O	O			O	X	
Slipping Belt	O	O	O		O		O	O	
Leaking Valves			O		O		O	X	
Unit Not Operational	O	X		O	O	O	O	O	O

Table 7: Required Data for Available Tools

O	Basic FDD
X	Extended FDD

	FDS Insight V.1 Production	Sentinel/Insight Beta Testing	ClimaCheck	SMDS	Sensus MI	NILM	Low Cost NILM	Virtjoule	Low Cost SMDS
Suction Pressure		O	O		X				
Discharge Pressure			O		X	O			
Suction Temperature		O	O		X				
Discharge Temperature		O	O		X				
Liquid Temperature		O	O		X				
OAT	O	O	O	O	O				O
RAT	O	O	O	O	O				O
MAT				O	O				O
SAT	O	O	O	O	O			X	
Condenser leaving air temp			O						
OARH					X				
RARH	O	O			X	O			
MARH				O	X				
SARH				O	X			X	
Damper Position			X	O				X	
Operating Mode	O	O	X	O	O				
Compressor Status			X	O	O				
Fan Status			X	O	O				
Vibration								O	
Fan, Compressor, or RTU kWh			O	O					O
Power factor						O			
Real/reactive power			O			O			
Power Quality						O			
Compressor Voltage									
Compressor Amperage									
RTU Voltage						O	O	O	
RTU Amperage	O	O				O	O	O	

4.4. Description of Potential FDD Approaches

For each cell in Figure 1, we describe the following aspects of the hypothetical, available, and developing tools:

- Required information: what information set does the system need to access? Some of this information is readily available from standard/higher end RTU control boards, whereas other information is obtained by the mean of additional sensors.
- Example of detected faults: this list of faults is based on publications detailing the operation of this FDD solution (if available) or engineering knowledge. This is by no means exhaustive but serves as an illustration of the potentialities of the system.
- Hardware requirements: based on the required information and the type of processing envisioned, it is possible to list the necessary components and an approximate price if available.

4.4.1. Refrigerant Quantitative Model Approach

This approach works by comparing performance indices calculated by an internal model on one side, and obtained by processing input values on the other side. By observing the residuals, it is possible to detect faults in the system

Required information

- Suction pressure*
 - Liquid pressure*
 - Discharge Pressure*
 - Suction temperature
 - Liquid temperature
 - Ambient temperature
 - Return air temperature
 - Supply air temperature
- *can be substituted with additional temperature sensors

Based on that information, the system can evaluate performance indices such as:

- Evaporation temperature
- Superheat
- Condenser temp
- Sub cooling
- Evaporator Delta T
- Condenser over ambient

Example of detected faults

- Faulty refrigerant charge

- Compressor valve leakage
- Liquid line restriction
- Condenser fouling
- Inadequate airflow

Hardware requirements & Pricing elements

- Temperature/pressure sensors
- data processing module in order to run the physical model
- Communication module (required for any FDD)

Example Available Tool: Sentinel and Insight

The Sentinel provided by Field Diagnostic Systems is an example of a refrigerant-side tool that uses quantitative methods to diagnose system condition. Due to the high cost of the Sentinel, with its requirement for a number of sensors to be installed, FDSI has developed the Insight analysis tool, which makes use of onboard sensors and data acquisition systems to provide the same diagnostics.

Example Available Tool: ClimaCheck

Description

This system developed in Sweden allows the continuous monitoring of refrigerant systems. Available either in portable or fixed installation format, the system is composed of the following elements:

- A data acquisition system (PA Pro)
- Power meter
- Temperature sensors
- Pressure sensors
- Climacheck software
- Optional LAN connection or GPRS modem

The system is based on an internal thermo physical model and can therefore be used on any kind of refrigerant system. It allows the user to assess system performance based on temperature, pressure and power measurements.

Because of its cost, this tool is applied most frequently as a service productivity tool, rather than an ongoing degradation detector. It is typically used in a service offering, in which an experienced technician uses the tool to efficiently assess the condition of one or more RTUs at a facility.

An evaluation of possible savings, documented in “Energy Optimisation Potential through Improved Onsite Analysing Methods in Refrigeration”, Arul Mike Prakash 2006, found that out of 49 analyzed air conditioning systems, 44 were found with faults. The most frequent faults detected were related to charge (70% of units), expansion valves (30%) and secondary flow (11%). No values on efficiency are documented, but an average variation in COP of -11.5% was documented.

Cost

A complete unit is around \$5000-\$6000

Energy savings: Case study

An evaluation of possible savings is documented in “Energy Optimisation Potential through Improved Onsite Analysing Methods in Refrigeration”, Arul Mike Prakash 2006

The most frequent faults were related to Charge (70% of units), expansion valves (30%) and secondary flow (11%).

Out of 49 analyzed air conditioning systems, 44 have been found with faults. No values on efficiency are documented, but an average variation in COP of -11.5% has been documented

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4.4.2. Refrigerant Qualitative Model Approach

This approach is very similar to the previously described “refrigerant quantitative” approach, as in both cases a set of performance indices is calculated. In this case, though, the value of these indices is compared to tabulated target values, and the difference observed for each of these indices is used in a rule based approach in order to identify the fault.

Required information

- Suction pressure*
 - Liquid pressure*
 - Discharge Pressure*
 - Suction temperature
 - Liquid temperature
 - Ambient temperature
 - Return air temperature
 - Supply air temperature
- * can be substituted with additional temperature sensors

Based on that information, the system can evaluate performance indices such as:

- Evaporation temperature
- Superheat
- Condenser temp
- Sub cooling
- Evaporator Delta T
- Condenser over ambient

Example of detected faults

- Faulty refrigerant charge
- Compressor valve leakage
- Liquid line restriction
- Condenser fouling
- Inadequate airflow

Hardware requirements & Pricing elements

- Temperature/pressure sensors
- data processing module
- Communication module (required for any FDD)

4.4.3. Refrigerant Timeseries Approach

In this case, no target for the performance indices is defined. The target values are obtained from the acquisition taking place during the first phase of operation.

Required information

- Suction pressure*
 - Liquid pressure*
 - Discharge Pressure*
 - Suction temperature
 - Liquid temperature
 - Ambient temperature
 - Return air temperature
 - Supply air temperature
- *can be substituted with additional temperature sensors

Example of detected faults

- Capacity to detect the following faults:
- Refrigerant leakage
- Compressor valve leakage
- LL restriction
- Condenser Fouling
- Inadequate airflow

Hardware requirements & Pricing elements

- Necessary addition of pressure sensors and/or additional temperature sensors => material and installation costs
- Data logger+ Simple signal processing (hardware for timeseries based approach)
- Communication module (required for any FDD)

4.4.4. Air Quantitative Model Approach

By simulating the behavior of the unit for the measured input conditions and comparing the calculated and measured supply air temperature, it is possible to detect faults within the system.

Required information

- outdoor air temp. (OAT)
- return air temp. (RAT)
- mixed air temp. (MAT)
- supply air temp. (SAT)
- fan status
- cooling/heating mode operation
- outdoor air damper position

Example of detected faults

- supply air temperature too high: inadequate airflow
- supply air temperature too low: incorrect refrigerant charge/ compressor leakage.

Hardware requirements & Pricing elements

- temperature sensors
- data processing module in order to run the physical model
- Communication module (required for any FDD)

4.4.5. Air Qualitative Model Approach

This approach would get rid of the physical model of the quantitative approach, and rely on the variation of parameters and predefined acceptable ranges for each parameter to detect a faulty operation. This would be much simpler but would only be practicable during steady state operation.

Required information

- outdoor air temp. (OAT)
- return air temp. (RAT)
- mixed air temp. (MAT)
- supply air temp. (SAT)
- fan status
- cooling/heating mode operation
- outdoor air damper position

Example of detected faults

- incorrect economizer set-point
- supply air temperature too high: inadequate airflow
- supply air temperature too low: incorrect refrigerant charge/ compressor leakage.

Hardware requirements & Pricing elements

- Temperature sensor
- Data processing module
- Communication module (required for any FDD)

Example Available Tool: Smart Monitoring and Diagnostics System

Description

Battelle Pacific Northwest Division in collaboration with NorthWrite Inc. has developed a tool for continuously monitoring the condition and performance of packaged air conditioners and heat pumps.

The Smart Monitoring and Diagnostic System (SMDS) is mounted in a small box installed on the side of each packaged air conditioner or heat pump and provides continuous remote monitoring and diagnostics for the unit. It requires the following components:

- Temperature sensor
- Data processing module
- Communication module (required for any FDD)

The SMDS works by constantly collecting data from sensors installed on the equipment to measure its performance and detect and diagnose problems with its operation. The unit then sends the results wirelessly, directly from each packaged unit to a network operations center, where the data are stored

securely and information on the condition of each packaged unit is made available on the internet. The SMDS can be installed on new or existing packaged air conditioners and heat pumps.

This approach gets rid of the physical model of the quantitative approach, and relies on the variation of parameters and predefined acceptable ranges for each parameter to detect a faulty operation. This would be much simpler but is only possible during steady state operation.

Cost Around \$2000/unit + \$200 to \$1000 for installation.

Other

The diagnostics that are provided in some high-end RTUs are an example of qualitative models that make use of air-side data. For example, the Carrier controller can provide an alarm if a filter is clogged and if an economizer is malfunctioning, based upon various sensor readings, and a qualitative model of variables such as high static pressures and no damper movement mean. The tables that follow provide the alarm codes that may be useful for energy management for four high-end RTUs:

Lennox Alarm Codes:

Alarm	Problem	Action
6	S27 (Dirty Filter Switch) This indicates a dirty filter.	None
59	Gas valve 1 not energized 3 (default) times (2 minutes after a demand). Check gas supply, ignition control and wiring. ECTO 3.09. (GV1)	Only action taken is storing code in memory.
75	Outdoor Temperature (RT17) Sensor Problem Check wiring and sensor.	The control defaults to a high outdoor temp. operation.
91	Outdoor enthalpy sensor (A7) open. Check sensor and wiring.	No economizer free cooling operation if economizer mode is set to ODE or DIF.
92	Indoor enthalpy sensor (A62) open. Check sensor and wiring.	No economizer free cooling operation if economizer mode is set to DIF.
93	The control has changed the system mode because of an error with the controlling sensor or because of a loss of communication	IMC has switched over to the backup mode option set with ECTO 6.01.
99	Outdoor Air Control Sensor (A24) open. Cleared by IMC reset.	No OAC operation. Damper closed to minimum position.

York Alarm Codes:

Alarm	Problem
Alarm 13	indicates the Space Temperature Sensor has failed open or shorted.
Alarm 14	indicates the Supply Air Temperature Sensor has failed open or shorted.
Alarm 15	indicates the Return Air Temperature Sensor has failed open or shorted.
Alarm 16	indicates the Outside Air Temperature Sensor has failed open or shorted.
Alarm 17	indicates the Dirty Filter Switch has tripped.
Alarm 1A	indicates a microelectronics failure and the control is operating on defaults.
Alarm 1D	indicates the Outside Humidity Sensor is out of Range.
Alarm 1E	indicates the Return Air Humidity Sensor is out of Range.
Alarm 1F	indicates the IAQ Sensor is out of Range.
Alarm 25	indicates the unit is locked out due either 1) high duct static pressure or 2) a faulty duct static pressure sensor with an output that is too high.
Alarm 26	indicates the control has detected a Supply Air Temperature fault for Cooling.
Alarm 27	indicates the control has detected a Supply Air Temperature fault for Heating.
Alarm 28	indicates the control has detected a Minimum Economizer Position fault condition.
Alarm 29	indicates the control has detected a Space Temperature Alarm condition.
Alarm 2A	indicates a fault with the Duct Static Pressure sensor reading a low pressure when there should be pressure present.
Alarm 2B	indicates the Hot Water Freeze Stat has opened, indicating a fault that could cause the coil to freeze.

Carrier Alarm Codes:

Alarm	Description	Probable Cause
T110	Circuit A Loss of Charge	Low refrigerant or faulty suction pressure transducer
T126	Circuit A High Refrigerant Pressure	An overcharged system, high outdoor ambient temperature coupled with dirty outdoor coil, plugged filter drier, or a faulty high-pressure switch.
T133	Circuit A Low Refrigerant Pressure	Low refrigerant charge, dirty filters, evaporator fan turning backwards, loose or broken fan belt, plugged filter drier, faulty transducer, excessively cold return air, or stuck open economizer when the ambient temperature is low.
T408	Dirty Filter	Dirty Filter
T414	Economizer Damper Actuator Out of Calibration	Calibrate economizer (E.CAL). If problem still exist then determine what is limiting economizer rotation.
	Economizer Damper Actuator Torque Above Load Limit Alert	Actuator load too high. Check damper load.
	Economizer Damper Actuator Hunting Excessively	Damper position changing too quickly.
	Economizer Damper Stuck or Jammed	No economizer motion. Check damper blades, gears, and actuator.
	Economizer Damper Actuator Mechanical Failure	Check actuator and replace if necessary.
	Economizer Damper Actuator Direction Switch Wrong	Actuator direction control switch (CCW, CW) wrong.

Trane Intellipak Alarm Codes:

Alarm
Blocked Air Return
Energy Recovery Wheel Proof Failure
Improper Airflow for Dehumid
Low Pressure Control Open - Ckt 1
Low Pressure Control Open - Ckt 2
Low Refrigerant Charge - Ckt 1
Low Refrigerant Charge - Ckt 2
Cond Sump Min Level or Drain Failure
CO2 Sensor Failure
Min OA Flow SETPOINT Failure
Min Position SETPOINT Failure
OA Temp Sensor Failure
Return Air Temp Sensor Failure
Supply Air Temp Sensor Failure

Trane Intellipak Alarm Codes Explained:

DIAGNOSTIC DISPLAYED	REASON FOR DIAGNOSTIC	UCM'S REACTION	RESET REQUIRED
Low Refrigerant Charge (Ckt1 and/or Ckt2) Problem: The difference between entering and leaving evaporator temperatures is greater than Evaporator Temperature Differential SETPOINT for 10 minutes. Check: Status of refrigerant charge and running pressures on affected circuit.	Low refrigerant Charge (Ckt1 and/or Ckt2). The cooling circuit has been active for 10 minutes and the difference in the entering and leaving evaporator temperatures is greater than the Evaporator Temperature Differential SETPOINT for 10 continuous minutes.	A "Lockout (Ckt1 and/or Ckt2)" request is issued to the compressor Staging Control Function.	(PMR) A manual reset is required anytime after the Diagnostic is set. The Diagnostic can be reset by the Human Interface or Tracer, or by cycling power to the RTM.
Minimum Outdoor Air Flow SETPOINT Failure Problem: The input designated as the SETPOINT is out of range. Check: Wiring to the GBAS input designated for Minimum Outdoor Air Flow SETPOINT or check BAS/Network interface card status and wiring.	Minimum Outdoor Air Flow SETPOINT out of range: OA flow is < 0 or > Max Unit Airflow (46000 CFM for 90 and 105 Ton and 58500 CFM for 120 Ton and up).	The active Minimum OA Flow SETPOINT reverts to the default Minimum OA Flow SETPOINT.	(PAR) An automatic reset occurs after the Minimum OA Flow SETPOINT input returns to within range for 10 continuous seconds, or after a different, valid Minimum OA Flow SETPOINT selection source is user-defined.
Supply Air Temperature Sensor Failure Problem: The Supply Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). Check field/unit wiring between Sensor and RTM.	The unit is reading a signal that is out of range for the Supply Air Temperature input on the RTM (Temperature < -55 F or Temperature > 209 F).	These unit functions are disabled; a. SupplyAirTempering b. Economizing c. On CV units, the Supply Air Temperature low limit function is disabled. d. On VAV units, the Supply Air Temperature Control heating and cooling functions are disabled.	(PAR) An automatic reset occurs after the designated Supply Air Temperature input returns to its allowable range. In order to prevent rapid cycling of the Diagnostic, there is a 10 second delay before the automatic reset.
Return Air Temperature Sensor Failure Problem: On units with the Comparative Enthalpy option, the Return Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). If so, check field/unit wiring between Sensor and ECEM.	The unit is reading a signal that is out of range for the Return Air humidity sensor (Temperature < -55 F or Temperature > 209 F).	The Economizer Enable r.e. Enthalpy function reverts to Reference Enthalpy changeover ("Level 2") control.	(PAR) An automatic reset occurs after the RA Temperature input returns to its allowable range continuously for 10 seconds.
OA Temperature Sensor Failure Problem: The Outside Air Temperature sensor input is out of range. Check: Sensor resistance should be between 830 ohms (200 F) and 345.7Kohms (-40 F). If so, check field/unit wiring between Sensor and RTM.	The unit is reading a signal that is out of range for the Outside Air Temperature sensor input on the RTM. (Temp < -55 F or Temp > 209 F).	Unit functions that are disabled include; a. Low Ambient Compressor Lockout b. The Outside Air Damper drivestominimumposition. c. On VAV units with SA Temp Reset type selected as OA Temp Reset, the Reset type reverts to NONE for the duration of the failure.	(PAR) An automatic reset occurs after the OA Temp input returns to its allowable range. In order to prevent rapid cycling of the Diagnostic, there is a 10 second delay before the automatic reset.

4.4.6. Air Timeseries Based Model Approach

In this case, there is no need of a physical model, and no maps, thresholds or set of rules have to be defined: the system logs the system state for different input conditions and defines patterns. If at some point during the system life the behavior of the system does not match these patterns, the system is considered faulty.

Required information

- Outdoor air temp
- Return air temp
- Mixed air temp
- Fan status
- Cooling/heating mode operation
- Outdoor air damper position

Example of detected faults

- Economizer errors or thermostat set point errors can be detected by comparing the mode of operation (cooling/heating, fan on/off, damper position) for similar OAT/RAT/MAT and schedule
- Capacity degradation can be seen from a variation in compressor cycling for similar OAT/RAT temperatures
- Fouled filter or other airway obstructions can be detected by an increased mixed air temperature for a given mode of operation and return/outdoor air temperatures

Hardware requirements & Pricing elements

- Factory sensors/information => no additional sensor required
- Data logger+ Simple signal processing (hardware for process timeseries based approach)
- Communication module (required for any FDD)

Example Available Tools: Sensus MI

Description

This product is entirely software based and leverages on the information already available through the BAS system

Cost

Very low due to low capital and installation costs: ROI < 1 year

4.4.7. Power quantitative model approach

This approach necessitates running a complete model taking into account the fluid dynamics, mechanic and electromechanical aspects of the system, in order to calculate the instantaneous power and required power requested by the unit. The level of complexity involved renders this approach impracticable.

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4.4.8. Power Qualitative Model Approach

In this case, the requested power profile of the unit is compared with target values stored into the controller for the different phases of the system.

Required information

Current and voltage sensors at the RTU feed. In case of three phase system, two of each is necessary.

Example of detected faults

Electrical/electromechanical RTU faults:

Fault	Diagnostic Method
Loss of phase	Current and Voltage
Locked rotor	Start transient
Slow starting motor	Start transient
Unbalanced voltage	Voltage
Short cycling	Event sequence
Motor disconnect/failure to start	Event sequence
Incorrect control sequence	Event sequence
Contactors (improper contact closure)	Phase current interruption transient
Fan rotor faults that result in imbalance	Amplitude spectrum in steady operation

Non-electrical faults:

Fault	Diagnostic Method
Refrigerant leakage, undercharge, or overcharge	Change of mean
Loss of volumetric efficiency (leaky valves, seals)	Start transient
Fouled condenser coil	Change of mean
Dirty supply air filter	Change of mean
Liquid ingestion *1	Anomalous transient
COP degradation *2	

**1 requires refrigerant flow (or compressor map) and head pressure*

**2 requires air-side flow and RH*

Hardware requirements & Pricing elements

- single-phase diagnostic can be implemented in a low cost 150 MHz PC-on-a-chip with a 2 channel A/D converter, with an incremental RTU manufacturing cost as low as \$200.
- Communication module (required for any FDD)

4.4.9. Power Timeseries Based Model Approach

Source: Armstrong et al. 2004 2006

This approach is based on NILM (Non Intrusive Load Monitoring), which is the measurement of power and reactive power used by the unit.

In this case, many faults are diagnosed by looking at transients, which implies a relatively high sampling frequency of around 120 Hz.

This method differs from the qualitative power approach since the target values are not entered as system parameters but are obtained from the first phase of operation.

Required information

Current and voltage at the RTU feed. In case of three phase system, two of each is necessary.

Example of detected faults

Electrical/electromechanical RTU faults:

Fault	Diagnostic Method
Loss of phase	Current and Voltage
Locked rotor	Start transient
Slow starting motor	Start transient
Unbalanced voltage	Voltage
Short cycling	Event sequence
Motor disconnect/failure to start	Event sequence
Incorrect control sequence	Event sequence
Contactors (improper contact closure)	Phase current interruption transient
Fan rotor faults that result in imbalance	Amplitude spectrum in steady operation

Non-electrical faults:

Fault	Diagnostic Method
Refrigerant leakage, undercharge, or overcharge	Change of mean
Loss of volumetric efficiency (leaky valves, seals)	Start transient
Fouled condenser coil	Change of mean
Dirty supply air filter	Change of mean]
Liquid ingestion *1	Anomalous transient
COP degradation *2	

*1 requires refrigerant flow (or compressor map) and head pressure

*2 requires air-side flow and RH

Hardware requirements & Pricing elements

- Single-phase diagnostic can be implemented in a low cost 150 MHz PC-on-a-chip with a two channel A/D converter, with an incremental RTU manufacturing cost as low as \$200.

- Communication module (required for any FDD)

Example Available Tool: Virtjoule

Description

This system would be composed of RTU power sensors, communicating with the Virtjoule gateway using ZigBee protocol. This allows the information to be shared with Virtjoule network operation center (NOC). Data is then processed and communicated to the end user via different possible channels (web-service, email, SMS...)

Approach

The basis for the analysis is the usage metering and power signature provided by the power sensor. This raw information, routed to the NOC, is then combined with additional data such as historic data or local weather information in order to detect and classify faults.

Cost

Typical ROI < 1.5yr

Example Available Tool: Non-Intrusive Load Monitoring

The Non-Intrusive Load Monitoring (NILM) device, developed by the Massachusetts Institute of Technology is an example of power-monitoring tool that uses timeseries-based methods to diagnose system condition.

This approach was first developed to investigate the energy use in whole buildings. It has been dubbed non intrusive because the hardware can be connected on the electric power supply to the house, as opposed to using end-use meters to every appliances in the house.

The only required sensors are current and voltage sensors on the system.

In looking at instantaneous real and reactive power, and knowing that each load has its own resistance, inductance, and capacitance characteristics, it becomes possible to single out each individual load.

In the case of packaged air conditioning units, the loads are limited to the compressors and fans. It is therefore easy to detect which component is running. If we combine this information to one or two air temperature measurements, it becomes possible to get an insight into the working conditions of the system, and changes of efficiency or major faults occurrences can be detected. Combining information on the power uses and outdoor air and return air temperatures, changes in energy efficiency and occurrence of major faults can be detected.

4.4.10. Hybrid Power/Airside Timeseries Based Model Approach

This approach focuses on reducing the cost of the device, and therefore focuses on faults that can be diagnosed by looking at event sequences. In this case, the system can be very simple since there is no need to measure the reactive power, and the sampling frequency can be also reduced (target: a few samples/minute).

This approach is called “hybrid” because it also requires some temperature information from the “air side” methods.

This approach is very close to the air side timeseries based model on both required information and the way this information is treated. The main difference is that the state of the fans and compressor is obtained from the power measured at the RTU feed.

Required information

- Power-meter
- OAT/TAT/MAT temperatures

Example of detected faults

- Efficiency degradation by increases in the total power use given the outdoor-air temperature
- Degradation in capacity from
 - Increase in on time per cycle for each specific outdoor-air temperature
 - Continuous operation without cycling at a lower outdoor-air temperature or lower outdoor-air enthalpy than previously observed
- Operation during unoccupied times (or incorrect schedule specification) via power level indicating supply fan, condenser fan, and compressor are operating during times when the building or specific building zones are not occupied.
- Excessive cycling indicated by compressor power cycling at a frequency higher than acceptable.
- Unit not operational - zero power during conditions (e.g., time of week and outdoor-air temperature) when the unit has historically operated.

Hardware requirements & Pricing elements

Power meter: the small number of electric components in a typical RTU (2 to 4) makes the identification of the running components straightforward, obviating the need to measure the reactive power. The requested temperature sensors are usually already available. The remaining hardware includes a transmitter, which cost may vary according to the technology used. Target price: \$100-\$400

Example Available Tool: Lo-Cost SMDS

The Low-Cost Diagnostic Module proposed by Pacific Northwest National Laboratory is an example of a power monitoring tool that uses qualitative methods to diagnose system condition from power monitoring and simple airside measurements.

5. Evaluation of Approaches

The sections that follow describe how well the different FDD approaches meet the criteria just discussed, and Table 8 below provides a summary of this assessment. Recall that we can only provide a qualitative assessment of most of the criteria, so we use a scale of High/ Moderate/ Low to describe whether each of the criteria are met fully, partially, or not at all.

Table 8: Summary of Evaluation of Different Fault Detection Approaches

● = High ○ = Moderate ◉ = Low

	Refrigerant Quantitative	Refrigerant Quantitative	Refrigerant Timeseries	Airside Quantitative	Airside Qualitative	Airside Timeseries	Power Quantitative	Power Timeseries	Hybrid Airside/Power Timeseries
Savings	●	●	●	○	●	●	●	●	●
Cost Eff	◉	◉	◉	○	○	○	●	○	●
Frequency	●	●	●	●	●	●	●	●	●
Fixed	●	●	●	○	●	●	●	●	●
Reliable	○	○	○	○	●	●	●	●	●
Deployable	●	●	○	●	●	○	●	○	○
Maint	●	●	●	●	●	●	●	●	○

5.1. Magnitude of Energy Savings

All approaches can offer significant energy savings. The Airside Quantitative approach provides somewhat lesser savings, because it has a limited number of situations it can diagnose. Most tools can identify refrigerant charge and airflow issues, which may have the potential for energy savings. Several methods can identify economizer problems, and only one (Hybrid Air/Power Timeseries Based) specializes in issues such as nighttime operation. Depending on the cost, it is likely that any of these methods would provide moderate or high energy savings, and would be suitable for inclusion in Title 24. The energy savings may not be dependable enough to drive marketability, however.

5.2. Cost effectiveness

The Power Qualitative and Hybrid Air/Power Timeseries Based models would seem to have the most potential to be cost effective. Since they require a very minimal set of data, the cost of acquiring data would be quite small. If they require significant hardware for processing, however, the costs will rise.

Most of the rest of the approaches would provide moderate level of cost effectiveness. They would have to be analyzed carefully to determine whether or not they were cost effective. The refrigerant based models, because of their requirement for a large number of sensors, can be expected to be less cost effective. If these data can be obtained inexpensively (for example, by being mass produced and installed in the factory, or by making use of existing sensors reliably as is done by FDSI's Insight and Sensus MI), then these methods may have some promise.

5.3. Frequency of Fault

All of the approaches address faults that have a significant frequency of occurrence. As described earlier, most existing RTUs can be expected to have one of the problems that each of these approaches can detect.

5.4. Probability that Fault will Get Fixed

Because most of the methods can detect issues such as incorrect refrigerant charge and the need for filter replacement, it is likely that the faults will be remedied once detected. Those faults are not necessarily the most important and energy intensive, however. Economizer malfunctions and certain airflow restrictions, which are a big source of energy waste, do not cause comfort problems and are more costly to address.

5.5. Reliability, Robustness

Because refrigerant data can be difficult to obtain accurately, the Refrigerant Cycle approaches have only moderate reliability. While Air Side data can also be difficult to obtain accurately, Qualitative and Timeseries Based approaches, which do not require the same degree of accuracy as Quantitative approaches, might be considered somewhat more robust. Power based approaches have somewhat less difficulty in installing, and are considered reliable.

5.6. Ease of Deployment

The deployment path for timeseries-based methods is more limited than for the other methods. Because they require a lengthy period of correct operation for training, and cannot be used in a Commissioning-type service, they can only be deployed in an ongoing performance monitoring or maintenance service.

5.7. Other Maintenance Benefits

From a Title 24 perspective, maintenance benefits are an added bonus. All of the tools that identify regular maintenance issues, such as charge and fouling, will provide benefits to the team that maintains the building. The hybrid method that identifies issues such as nighttime operation would provide less of a maintenance benefit.

6. Conclusion

By providing a comprehensive classification for available and hypothetical FDD tools, we have been able to identify which approaches seem the most promising—which available tools might be suitable for marketization or for inclusion in standards.

6.1. Highest Priority Approaches

Through this process, we have identified five approaches that appear to be most likely to be appropriate.

Power Qualitative: One of the high scoring approaches is the Power Qualitative approach. The power profile of the unit is compared with target values stored into the controller for the different phases of the system. This is able to detect a large range of refrigerant and airside problems, in addition to electrical and controls faults. This approach has many benefits. It can be quite cost effective, since it requires only one sensor and can detect a large number of faults that create energy waste in a large fraction of buildings. It would be difficult to install incorrectly, since it only has one sensor, and it can start immediately in detecting faults (without the requirement for a training dataset). Such a tool would provide a great deal of information to building operators and service contractors. NILM, developed by MIT is an example of this approach.

Hybrid Airside/Power Timeseries Based: Another high scoring approach is this one, which uses a dataset consisting of air-side and power data to identify a limited set of faults. The faults include overall efficiency degradation, capacity degradation, operation during unoccupied times, and excessive cycling. While it cannot identify some of the faults that are identified by most of the other approaches, addressing this set of faults can be expected to save quite a bit of energy. The simplicity of this approach is appealing, and it should be quite reliable. Because it cannot be used in a commissioning-like service, it is considered less deployable, and because the faults it detects are “silent” faults that do not affect comfort or equipment condition, it may not be considered highly marketable. The Low-Cost SMDS proposed by PNNL is an example of this approach.

Power Timeseries Based: This approach requires looking at power at relatively high sampling frequency in order to detect faults that are expressed during transients, in addition to those found by looking at mean values. It requires only one datapoint, but high frequencies require a different processing platform, increasing the cost. It should be able to detect a long list of faults and save quite a bit of energy. Because of its simplicity, it will be quite reliable, and it will provide a great deal of maintenance information to service providers. The fact that it cannot be used in a commissioning-like service makes it somewhat less deployable. The Low-Cost NILM developed at MIT, and the Power Analyzer being developed by Virtjoule are examples of this approach.

Airside Qualitative: The variation in air-side parameters is compared with predefined acceptable ranges to detect faulty operation. This can detect important and common issues such as economizer faults, refrigerant charge errors and coil fouling. It is reliable, due to the fact that the data inputs have less stringent accuracy requirements. The only downside to this method is its cost effectiveness. Care will have to be taken to ensure that tools in this category are cost effective. The System Monitoring and Diagnostic System developed by PNNL is an example of this approach.

Airside Timeseries Based: This system logs the system state for different input conditions and defines routine patterns. When a fault occurs, such as economizer errors, charge errors, or coil fouling, it can be detected as a deviation from the pattern. These models have the benefit of simplicity, and ability to detect important and frequent faults. They too have only moderate cost effectiveness, and care will have to be taken to ensure that tools are cost effective. Because they require a long period of proper operation to train the system, their deployment model is less obvious. Sensus MI is an example of this approach.

While we have characterized and evaluated generic and “hypothetical” approaches to FDD, it is certainly possible that individual approaches can overcome some of the hurdles faced by their category of approach. For example, if the cost and complexity of refrigerant-side measurements could be reduced, they could be very good candidates for code inclusion. FDSI’s Insight is an example of an approach that may have promise if it can use existing sensors.

6.2. Next Steps

The next step, described in the next section of this report, is to define a set of capability requirements that will provide the basis for the code language. This requirements document will be vetted with industry stakeholders in a Roundtable meeting. Coming out of this meeting will hopefully be a consensus as to the appropriate level of requirements for Title 24. We will then work to draft the proposed code language, ACM descriptions, and forms, and take this proposal through the CEC rulemaking process.

If we do not find sufficient appropriate tools, we will still develop a set of requirements and hold a stakeholders meeting. Again, we will drive towards a consensus on what *should* be in Title 24 *someday*, even though there are not tools that can meet these requirements. We will then put together a plan to move the industry forward so that tools meeting these requirements can be developed and the requirements can be adopted in the next round of revisions.

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DRAFT

**Public Interest Energy Research (PIER) Program
PROJECT REPORT**

**Fault Detection and Diagnostics:
Moving the Market and Informing
Standards in California
C: Draft FDD Standard for Rooftop Units**



A Report of the Western Cooling Efficiency Center

RESEARCH • INNOVATION • PARTNERSHIP

Prepared for: California Energy Commission

MARCH, 2011

Prepared by: Western Cooling Efficiency Center

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DRAFT

DEVELOPMENT OF A DRAFT FDD STANDARD FOR ROOFTOP UNITS

In this third Phase, we have developed a draft specification for new requirements for FDD in Rooftop Units. We have also held an industry roundtable to present the draft to a set of industry actors, and obtain their feedback. The next phase of activity, described in a separate report, will consist of drafting a formal proposal for a standard and following the CEC Title 24 review process.

Remote and automated Fault Detection and Diagnostic (FDD) tools have the potential to save considerable energy in California fleet of existing commercial rooftop air conditioning units (RTUs). The market for these systems has not yet materialized, however. Tools have been available for larger systems for some time, although even these have not enjoyed a significant market share. In RTUs, there are fewer tools available, and little to no market share.

Since RTUs cool over 70% of the commercial square footage in California, they are a significant source of energy consumption and peak demand. Under the best of circumstances, RTUs are not as efficient as larger built up systems. However, in reality, they are even less efficient. Many market failures have led to a lack of quality in installation and maintenance of these units, and their performance is suffering. Most RTUs have some sort of fault that is increasing their energy use. If these faults could be found and addressed, then energy savings could be realized.

In “Fault Detection And Diagnostics, Moving The Market And Informing Standards In California Deliverables: FDD Prioritization,” we identified nine different potential approaches, depending on the type of data collected (air side, refrigerant side, or electrical) and the type of model used for comparison with measurements (first principles, qualitative, history). We also identified the specific criteria that must be met to have a measure that is appropriate for inclusion in Title 24. These criteria included significant energy savings, cost effectiveness, prevalence of the fault being detected, probability that the fault will be fixed, reliability of detection, deployability, and other maintenance benefits.

The faults that can be detected by various FDD tools include efficiency degradation, low charge, coil fouling, filter dirty, insufficient capacity, excessive operating time, incorrect control sequence, lack of ventilation, insufficient economizing, unnecessary outdoor air, failed sensor, control problems, failed compressor, stuck damper, slipping belt, leaking valves, short cycling, unit not operational. The tools that are available are shown below:

Tool Name	Status	Data	Model	Developer
FDSI Insight V.1	Available	Refrigerant	Quantitative	Field Diagnostics, Inc
Sensus MI	Available	Air	Qualitative	University of Nebraska
ClimaCheck	Available	Refrigerant	Quantitative	ClimaCheck Inc.
SMDS	Pilot	Air	Qualitative	Pacific Northwest National Lab
NILM	Pilot	Power	Qualitative	Massachusetts Institute of Technology
Low Cost NILM	Pilot	Power	Timeseries	Massachusetts Institute of Technology
Sentinel/Insight	Beta	Refrigerant	Quantitative	Field Diagnostics, Inc
Virtjoule	Developing	Power	Timeseries	Virtjoule Inc.
Low Cost SMDS	Developing	Air-Power	Timeseries	Pacific Northwest National Lab

Draft FDD Standard for Rooftop Units

In order to develop a draft specification for a RTU FDD standard, we have undertaken several tasks. We reviewed the current optional requirements for FDD in Title 24 (2008) to determine the level of specificity that the new requirements might entail. We developed a short summary of the existing standard that includes all of the requirements contained in the Standard, the ACM, the User's Manual, and the Acceptance Test Forms. We revised this summary to include the new requirements we felt might be included in a new standard. The document shown in Attachment 1 is this summary. **(NOTE that this Proposal was updated Feb 2011 after subsequent stakeholder input).**

Industry Roundtable

An Industry Roundtable was held at the Western Cooling Efficiency Center, UC/Davis on July 22, 2010. The attendees are shown in Attachment 2.

Summary of Discussion

The discussion among participants both in person and those remotely was wide and deep, limiting this report to a high level summary. What follows are key takeaways and issues identified to follow up on for both the PIER and CASE team researchers. We will be contacting individual participants for further discussion about comments made at the Roundtable and those received pre- and post-roundtable. We very much appreciated the positive tone of the meeting. This is a complex topic, as all of you all understand. There are different needs for different markets that have to be accounted for and balanced in setting standards. For example, Walmart needs an approach to manage the 25 million HVAC alarms generated company-wide in 2009. The company needs intelligence that manages and reduces alarms, not necessarily additional sensors and algorithms that add to them. Compare this with the owner of a suburban 10,000sf, two-story office building with a handful of RTUs, who would benefit from basic FDD functionality in the RTUs such as monitoring airflow, economizer operation, sensor malfunction, refrigeration charge status and not a whole lot more.

The tenor of the meeting was very positive. Overall, the researchers got the message to:

- Proceed with the potential for a 2011 Title 24 Prescriptive Measure
- Provide substantiation of:
 - FDD energy savings benefits and persistence
 - FDD product availability, in the market or on the way
 - FDD product costs including communications gateway
 - Fault priorities/prevalence
- Take the RTU FDD discussion national including the manufacturers and ASHRAE 90.1

In summary, participants collectively took a useful step on the path toward increasing, maintaining and controlling the energy efficiency of RTUs through FDD methods as a component of enhanced performance monitoring and performance measurement.

Key Takeaways (summarized as offered at the end of the meeting)

- a. As an alternative first step, explore an approach to first capture the data, perhaps in the T-stat, before analysis methods are standardized. How long to store data? Who collects/analyzes? How does it become actionable information?
- b. Move toward a 2011 T24 Prescriptive Measure submission; it's possible, but challenging.
- c. It was noted by the manufacturers that "the hardware is the easy part," and by the FDD tool developers that "we can't manufacture this in a big way tomorrow." Partnering may be required to move this technology into the market quickly.
- d. Initiate an 'FDD Challenge' similar to the idea of the Western Cooling Challenge, to pull the products into the market more quickly and at the same time, work to condition the market for the products. This might happen in cooperation with the Retailer Energy Alliance that US DOE supports.
- e. Assess both a 'performance degradation factor' and a "performance index" as a potential overall performance monitoring/fault condition indicator to the RTU owner/manager/servicing contractor. What is the threshold definition for detecting faults that drive the degradation factor? How low is too low?
- f. Further prioritize the faults in severity and frequency. There are other performance issues that are not on the list in the Strawman.
- g. It's a complicated picture with the manufacturers, entrepreneurs, customers, and utilities all having separate driving interests.
- h. Engage the utilities Emerging Technology programs for proof-of-product and then potentially tap into utility incentive programs and then into Title 24.
- i. FDD is an enabling technology. While we can't make anyone use the information that is or will be available from this type of monitoring, the fact that the information exists drives the potential for market understanding and enables action. Some factor must be developed to account for this indirect benefit.
- j. Sensor accuracy/persistence is unquestionably an issue and is being addressed by ASHRAE. We need to get up to speed on this activity.
- k. Pick the top four faults in the Strawman along with Performance Degradation indicator and that's enough.
- l. Take this discussion national to bring in additional manufacturers of FDD products. Need the FDD business case and volume business to catch industry attention.
- m. RTUs can be split into those with electro-mechanical controls or with microprocessor controls. This dictates what is possible with sensing and communications.
- n. Transmit the performance data/alarms/FDD off the roof for remote viewing. Webenabled is a real option.
- o. Title 24 standard should not be too prescriptive. Try to specify performance objectives within the prescriptive measure. This can drive new technology solutions.
- p. FDD should be integrated with Quality Installation practice

Quotable Quotes

- q. “The California Reach Code is not a dumping ground for unsupported measures.”
- r. “FDD needs to be developed into an iPhone or iPad app.”
- s. “Innovation comes into the market at the speed of profits.”

Next Steps

The next steps in this research project, to be described in future documents, include:

- *Quantify the expected energy savings and costs of systems.* By conducting a survey and analysis of system costs, and simulating the savings attributable to FDD, we can estimate the cost effectiveness in a typical building. This modeling may also be used to determine savings from implementing FDD in a specific RTU, for compliance purposes. This work will be done in parallel with the next step, and will be complete in the first quarter of 2011.
- *Discuss with industry stakeholders to get additional feedback on the draft requirements.* The draft standard will be disseminated widely and feedback from a range of stakeholders will be taken into account in developing a Code Change Proposal. This will be done in parallel with the first step and will be complete by the end of the first quarter of 2011.
- *Develop a formal Code Proposal.* Once all possible input has been obtained on the draft standard, a formal Code Change Proposal will be developed. This will be done in conjunction with Portland Energy Conservation, Inc. The role of the CEC team will be defining requirements and reviewing draft proposals. This will be completed by April of 2011, or whenever the deadline is for submission of proposals.
- *Follow the CEC review process.* The interviews and analysis conducted by the CEC team are part of the due-diligence that is required for any Code Change proposal. This process also includes formal stakeholder workshops and an open comment period. The CEC team will participate in these workshops and responding to questions, as needed and appropriate. This is expected to occur in April of 2011.

Attachment 1: Proposed FDD Standard for RTUs

2011 Title 24 for Nonresidential Buildings requires installation (factory or field), verification, and acceptance testing of a Fault Detection and Diagnostics (FDD) system for Packaged Direct-Expansion Units, as a prescriptive measure. As with any prescriptive measure, this measure can be traded off for another optional measure with equal savings. Credit is given using the Alternative Calculation Method by degrading cooling efficiency by XX% for non-FDD systems and only 5% for FDD systems. This measure supplements the compliance option on Form MECH-12A first included in 2008.

FDD capabilities must be verified in the field by verifying that the FDD hardware is installed and that the equipment make and model includes factory-installed hardware that match the information specified on the manufacturers' cut sheets and design plans. The functionality of the FDD must also be tested in the field. Form **MECH-XXA** is used to verify that the criteria are met.

Construction Inspection

1. The following **sensors** should be permanently installed to monitor system operation and the controller should have the capability of displaying the value of each parameter:

Refrigerant Pressure	Refrigerant Temperature	Air Relative Humidity	Air Temperature
• Suction Line	• Suction Line	• Outside Air	• Outside Air
• Liquid Line	• Liquid Line	• Supply Air	• Return Air
			• Supply Air

2. The controller will provide **system status** by indicating the following conditions:

• Compressor Enabled	• Free Cooling Available	• Heating Enabled
• Economizer Enabled	• Mixed Air Low Limit Cycle Active	

3. The unit controller shall have the capability to **manually initiate each operating mode** so that the operation of compressors, economizers, fans, and heating system can be independently tested and verified.
4. The unit controller shall have the capability to **detect at least ten of the following faults**:

• Air Temp. Sensor Failure/Fault	• High Refrigerant Charge	• Low Refrigerant Charge
• Compressor short cycling	• Refrigerant Line Restrictions/ TXV Problems	• Refrigerant Line Non-Condensables
• Low Side HX problem	• High Side HX problem	• Capacity Degradation
• Efficiency Degradation	• Not Economizing When it Should	• Damper Not Modulating
• Excess Outdoor Air		

5. Faults shall be reported to a **fault management application** accessible by day-to-day operating or service personnel, or annunciated locally on zone thermostats.
6. A **performance indicator** shall be provided, which will allow tracking of efficiency.
7. The FDD System used shall be **certified by the CEC and verified to be installed correctly**. *Certification and verification procedures are TBD.*

Attachment 2: Roundtable Participants

Mike Brambley	Pacific Northwest National Lab
Martha Brook	California Energy Commission
Cathy Chappell	Heschong Mahone Group
Mark Cherniack	New Buildings Institute
Bobby DiFulgentiz	Lennox Industries
Martyn Dodd	EnergySoft
Piotr Domanski	National Institute of Standards and Technology
John Douglas	Lennox Industries
Joseph Fleishman	California Energy Commission
Craig Fulgum	Virtjoule
Tom Garcia	CalBO
Sean Gouw	Southern California Edison
Dale Gustavson	Better Buildings Institute, Inc.
Kristin Heinemeier	Western Cooling Efficiency Center
Randall Higa	Southern California Edison
Sherry Hu	Pacific Gas & Electric
Marshall Hunt	Consultant
John Kaufmann	Pacific Northwest National Lab
Golam Kibrya	California Energy Commission
John Kimmes	Target
David Kuo	Johnson Controls
Don Langston	Aire Rite Air Conditioning & Refrigeration, Inc.
Richard Lord	Carrier Corporation
Mike Lubliner	Washington State Energy Extension
Jim McClendon	Walmart
Jon McHugh	McHugh Associates
Jeff Miller	California Energy Commission
John Proctor	Proctor Engineering Group
Mark Rehley	Northwest Energy Efficiency Alliance
Todd Rossi	Field Diagnostic Services, Inc.
Chris Scruton	California Energy Commission
Vern Smith	Architectural Energy Corporation
Danny Tam	California Energy Commission
Stuart Tartaglia	Pacific Gas & Electric
Buck Taylor	Roltay Services, Inc.
Adrienne Thomle	Honeywell
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Stuart Waterbury	Architectural Energy Corporation
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